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Fast method to determine the structural defect density of 156 x 156 mm² mc-Si wafers

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Abstract

Today a remaining challenge is to determine the structural defect density (SDD) on a whole 156 x 156 mm² multicrystalline (mc) silicon wafer over a timescale of a few minutes. In this contribution a new method is introduced to determine the SDD on large scale mc-Si wafers. The main advantage of the method presented is the possibility to obtain a complete map of the SDD of a 156 x 156 mm² mc-Si wafer as well as a quantitative SDD analysis of the wafer in just a few minutes. Furthermore, the simple and quick sample preparation as well as the application of standard measurement equipment results in a convenient and cost-effective analysis tool. With these advantages, analysis of SDDs on large quantities of wafers, e.g. across the ingot height or width, can be easily realized in a few hours.

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1. Introduction

Today the majority of crystalline solar cells is based upon multicrystalline (mc) silicon. A remaining challenge of mc-Si is that it contains considerable structural defects seen as grain boundaries or dislocations. These defects are known to be able to reduce the minority carrier lifetime due to recombination activity and therefore limit the solar cell efficiency.

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Recent investigations using photoluminescence (PL) imaging revealed that V_{OC} decreases significantly due to an increasing amount of recombination active defects in the solar cell being mainly related to the recombination activity of structural defects [1]. Furthermore, it could be revealed that structural defects exhibit different recombination strengths on cell level, called type A and type B defects. Type A and type B defects exhibit recombination activity in mc-Si solar cells. Nevertheless prior to the cell process, type A defects are often not even visible in the PL image [2, 3]. This could be one reason why the prediction of V_{OC} from defect analysis of as-cut wafer PL images exhibits a significant scatter or even fails [4].

Another method to determine the SDD is based upon chemical delineation of the structural defects and the analysis of the laser light scattered by the etch pits. The preparation steps and the scanning time are fairly time consuming, leading to an analysis time of several hours for one mc-Si wafer [5, 6].

But to evaluate crystallization experiments and possible improvements concerning structural defects it is necessary to check the SDD of several wafers per brick and several bricks per ingot to get a significant conclusion. Therefore a time-saving method for SDD analysis is necessary.

In this contribution we want to introduce and describe a method that is mainly based upon chemical treatment and image processing to meet industry demands for a quick, cheap and easy method of analyzing the SDD of mc-Si wafers. This tool is much quicker than comparable methods which require several hours for the analysis of one single mc-Si wafer. We will present a detailed description of the SDD method and show several results of our investigations.

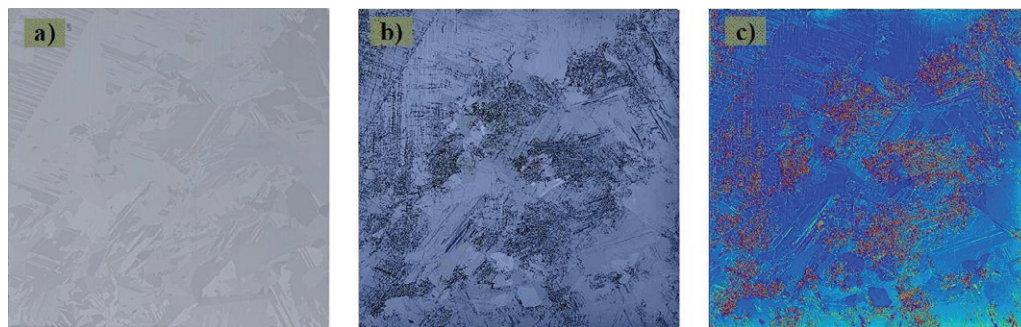


Fig. 1. Scanned image of an as-cut mc-Si wafer (a), the same wafer being scanned after acidic texturization (b) revealing areas of high SDD as dark regions, and the image after image processing (c) depicting the high SDD in red color

2. Method

To obtain a map of the structural defect density (SDD) (see Fig. 1c) of a 156 x 156 mm² as-cut mc-Si wafer (Fig. 1a) a modified acidic texturing process for silicon wafers is used resulting in deeper etch grooves due to preferential etching of structural defects as compared to an acidic texturization in the production line. This modified texturing process uses a mixture of HF, HNO₃ and H₂O in a laboratory wet bench [7]. In order to obtain comparable etching results from different experiments all samples must be treated equally. The latter is achieved by processing a test batch of dummy wafers prior to every SDD experiment, where the etching period is optimized to yield equal etch pit diameters in every experiment. This is the main factor for a good reproducibility. In the results presented below we have aimed at 6 μm diameters. Adjusting the etch pit diameter takes some minutes but is necessary to ensure that almost all surface crossing structural defects such as dislocations or grain boundaries are delineated.

After the acidic chemical treatment these structural defects become visible as dark regions. An image of the etched wafer can then be recorded by a commercially available flat-bed scanner (Hewlett Packard

Scanjet 4850) within a few seconds using a resolution of ~ 500 dpi (Fig. 1b). This setup is a compromise between scanning time, image file size and a sufficient resolution for the following image processing. The picture of the scanned wafer is then analyzed using the open source software *ImageJ* [8]. The image process assigns different colors to different severities of SDDs. This means, the scanned image will be converted into an 8-bit image with 256 different grey values from 0 (=black) to 255 (=white). The larger the structural defect density the smaller the grey value, meaning SDDs appear as dark areas.

The 256 grey values have been divided into five intervals. Every interval has been assigned to a different color. For the largest SDD $> 5 \times 10^6 \text{ cm}^{-2}$ red has been chosen followed by orange and yellow ($\sim 5 \times 10^6 - 10^5 \text{ cm}^{-2}$) and finally green and blue ($\leq 10^5 \text{ cm}^{-2}$) for the lower SDD resulting in a colored SDD map (Fig. 1c). The coloring process of an 8-bit image as described above can be realized by the *ImageJ* mode *Look-Up Table Panel* (LUT). Furthermore, the colored SDD maps are referred to as LUT images. Note that the density values associated with the colors are rough estimates based on comparisons of LUT images and defect-etched neighbored wafers on a microscopically scale, see Fig. 2. Therefore grain boundaries and twins as well as dislocations are counted [9]. Subsequently, the area fraction of each color on the whole wafer surface has to be determined. This is essentially achieved by counting the number of pixels of each color in relation to the $156 \times 156 \text{ mm}^2$ surface area. To obtain a quantitative analysis of the different SDDs, histograms of the LUT images have to be exported to data processing software such as Microsoft Excel[®].



Fig. 2. Detail of a dislocation density map (LUT image) (a) in comparison to the optical microscopy image of the same wafer region being acidic textured (b) and a neighbored polished wafer treated with a defect etch as described in [3] (c)

Since all surface crossing structural defects are delineated by the texturization process, twin boundaries are also detected although they are known to be “perfect” grain boundaries with weak or even no recombination activity [10]. However, twins are often categorized by the image processing as red areas, thus being erroneously interpreted as bad regions (Fig. 3a). In order to prevent such a systematic error due to twin boundaries, we improved the image processing routine to remove large number of the twins. This complex process routine also has been realized with *ImageJ*.

For this process, it is necessary to set a threshold to obtain a binary image where the black areas represent the structural defects. Then, with different filter functions, it is possible to highlight the twins, since twins appear as comparably long straight lines. Dislocations and grain boundaries on the other hand, often show a more randomly shaped structure and can be identified on this basis. This leads to a pure twin map, which will further be inverted in such a way that the twins appear white. The final step is to add the inverted twin image to the original 8-bit scan image with the *ImageJ* implied image calculator. The result is depicted in Fig. 3b, where twins are represented as blue areas and thus not being interpreted as bad regions anymore. Hence, the error in analyzing the SDD is reduced.

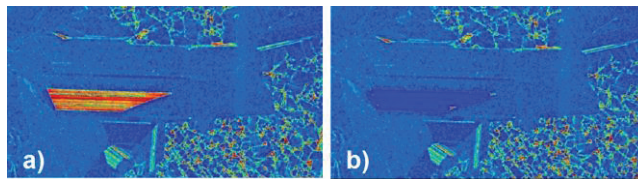


Fig. 3. (a) LUT image detail showing a region of twin boundaries erroneously colored red by the first version of the image processing routine, (b) after improving the routine, most of the twin boundaries are filtered out and are displayed as blue areas

3. Results & Discussion

The first and most important result of this investigation is that the entire analysis from the as-cut wafer to the SDD map including the quantitative analysis of the different SDD only takes a few minutes per wafer. The chemical treatment and the preparation steps prior to the scanning are the most time consuming processes. Nevertheless a SDD analysis of a 156 x 156 mm² mc-Si wafer on a timescale of minutes is much faster than comparable “large area”-methods based on a similar sample preparation which can take several hours to obtain the structural defect density of a single wafer [5, 6]. Investigations of SDD distributions over a complete brick height for numerous bricks or ingots can be accomplished within a few hours due to the comparably short analysis time.

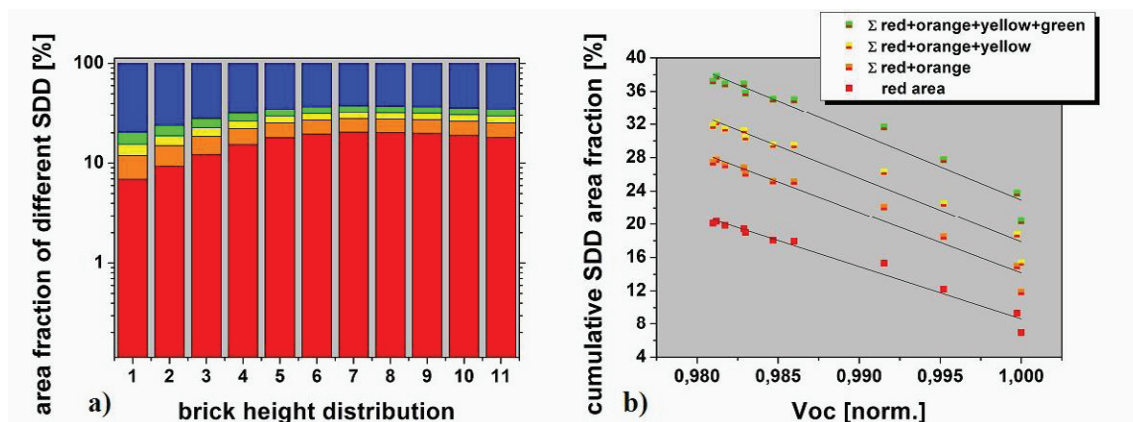


Fig. 4. Result of the SDD analysis of the LUT image on a logarithmic scale for eleven mc-Si wafers showing that the bottom wafer 1 contains a high SDD (red color) of 2.7% increasing to 11.0% in top wafer 11 (a) and correlation of the different SDDs of Fig. 4 with the V_{OC} of directly neighbored solar cells (b)

In Fig. 4a the quantitative SDD analysis for eleven wafers of one brick is depicted representing the SDD distribution over the brick height. A semi-logarithmic scale is used to emphasize the small wafer-area fraction of red color (high SDD) compared to the large blue area fraction (low SDD). In Fig. 4b the different SDDs have been accumulated and plotted as a function of the open circuit voltage V_{OC} of solar cells made from directly neighbored wafers. For every SDD category as indicated by the different colors a linear correlation is apparent.

For detailed information of the dependence of V_{OC} on the SDD the correlation factor R^2 has been used as a measure of the quality of the correlation. This analysis reveals almost identical R^2 values for all cases so that we decided to use the red area fraction for further analysis and for comparison with cell

parameters like V_{OC} . The blue color has not been analyzed since it represents the areas with the lowest SDD and correlates inversely with the open circuit voltage.

As one result of our investigations, the red area distributions of wafers from three different mc-Si bricks containing very high SDD are depicted in Fig. 5a. As can be seen, in all three cases the SDD increases with increasing brick height and sometimes reaches a maximum before dropping slightly towards the very top. This effect is often observed in edge or corner bricks due to nucleation sites at the crucible wall. Here, new grains begin to grow from the side into the ingot exhibiting very low SDD similar to grains nucleating at the bottom of the ingot.

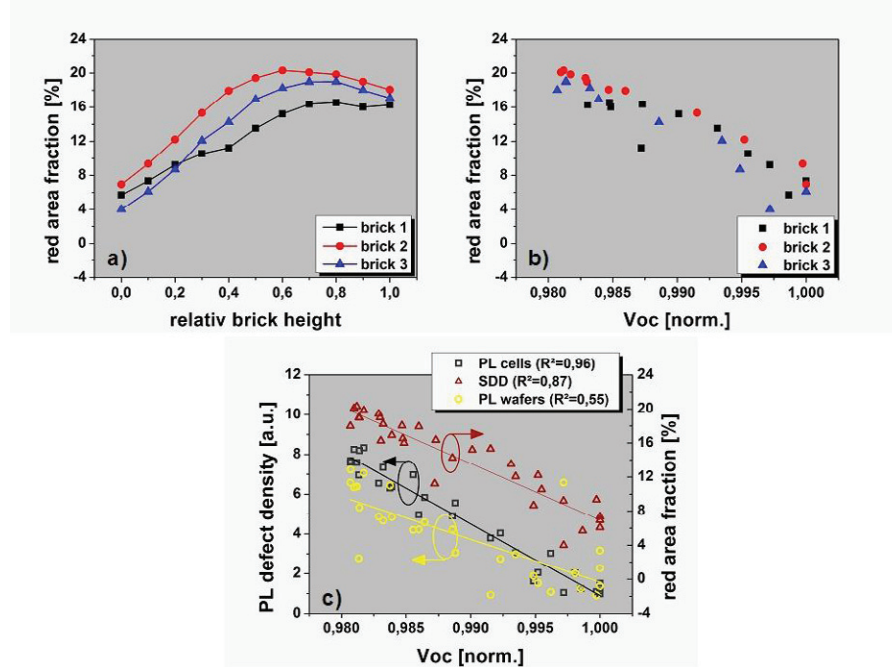


Fig. 5. (a) red area fraction (high SDD) distribution over the brick height of three bricks of different mc-Si ingots and (b) linear correlation between the open circuit voltage from cells produced from neighboring wafers and the red area fraction. (c) PL defect density and SDD red area fraction of the three analyzed bricks are depicted as a function of the normalized V_{OC} and have been fitted linearly to obtain the correlation factor R^2 for each defect analysis

Despite this fact, a strong correlation between the red area fraction and the V_{OC} was observed for the three investigated bricks as depicted in Fig. 5b. Further, we compared the SDD results with PL imaging defect analysis (Fig. 5c) [3]. Again the correlation factor R^2 is used revealing the near perfect ($R^2 = 0,95$) correlation between PL of solar cells and V_{OC} . The PL measured on neighboring wafers reveal a quite low correlation with $R^2 = 0,55$. The SDD method reveals a good correlation of $R^2 = 0,87$. For the three analyzed bricks the SDD method reveals a comparably higher correlation between defects and V_{OC} than the PL analysis of wafers. This is probably due to the fact that recombination active defects of type A are visible in the SDD method but to a certain degree not in the PL imaging of wafers.

4. Summary

We have presented a powerful tool to overcome the lack of a convenient and reliable method to analyze the structural defect density of complete 156 x 156 mm² mc-Si wafers in a low-cost and time

saving way. The method is based upon a chemical treatment, followed by an image scan and image processing that can be done within a few minutes for each mc-Si wafer. The presented results reveal that the SDD increases with increasing brick height and sometimes slightly drops in the top of corner or edge bricks. Furthermore we could correlate the structural defect density linearly with the open circuit voltage. A comparison using PL-imaging for the defect analysis on the same wafers, we find a better correlation with V_{OC} applying our method. This could be attributed to the properties of type A defects, which are due to structural defects but often are not recombination active prior to the cell process and thus not detectable by PL imaging.

Acknowledgements

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